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Extinction of CD band emission in the divertor of ASDEX Upgrade

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Abstract

We found a complete extinction of the CD molecule emission in the inboard divertor of ASDEX Upgrade at high density with the transition to a recombining divertor plasma. The electron temperature in the recombining divertor plasma ranges from 1.2 down to 0.3 eV. Two effects may explain the extinction at such low temperatures, (1) a steep decay of the yield for chemical sputtering as theoretically predicted and (2) a suppression of the optical emission while the methane molecules dissociate unchanged via charge exchange.

Keywords: Chemical sputtering; Divertor; Detached plasma

1. Introduction

In recent years, chemical erosion of carbon was intensively studied because of the intended use in the ITER experiment as divertor target material. Mainly the flux dependence of the chemical erosion was investigated. In the linear plasma generator PSI-1, the following relation for the sputtering yield was found $Y_{\mathrm{chem}} \propto \Gamma^{-0.6}$ [1]. The electron temperature T_e was held constant while the ion flux was varied. Because T_e determine the sheath potential in which the ions gain their energy, the flux dependence of the sputtering yield was determined for a constant energy of the incident ions (about 15 eV).

In a tokamak experiment, it is not possible to hold the divertor temperature constant during a density variation. In [2], the impact energy of the ions was estimated from target fluxes of ions and energy. By a regression analysis, a similar flux dependence was found ($Y_{\mathrm{chem}} \propto \Gamma^{-0.7}$) but no variation of the sputtering yield with the energy of the incident ions. This result was obtained in the outer divertor of ASDEX Upgrade, which is the hotter one in standard configuration (single *X*-point at bottom, ion grad B drift downward) [3]. The temperature was in the same order of magnitude than that realized in the PSI-1 device. Electron temperatures in the inboard divertor, however, can be lower by more than a magnitude [4]. In this paper, we will analyze the optical emission of the CD molecule (a dissociation product of methane) from the inboard divertor at very low temperatures.

2. CD emission from the inboard divertor

At high densities, the emission of the CD molecule is extinguished in the inboard divertor of ASDEX Upgrade. We consider the Ohmic standard discharge (Fig. 1). Between 1 and 2 s, the density is 3×10^{19} m^{-3}. At 2 s, the gas valve is closed and from 3 s onwards the density is ramped up to the density limit. Fig. 1 shows the spectroscopic signals of the CD band at 431 nm and D_γ, measured viewing with a scanning mirror spectrometer from the top of the vessel. Every time the line-of-sight strikes the inboard divertor, there is an emission peak either in CD or D_γ intensity. For geometrical reasons, the outboard divertor cannot be observed with this instrument. Fig. 2 shows the corresponding CD band intensity over the deflection angle of the mirror. The contour of the divertor is also given in these coordinates. During the density ramp-up, the divertor plasma becomes recombining as indicated by the increase of the

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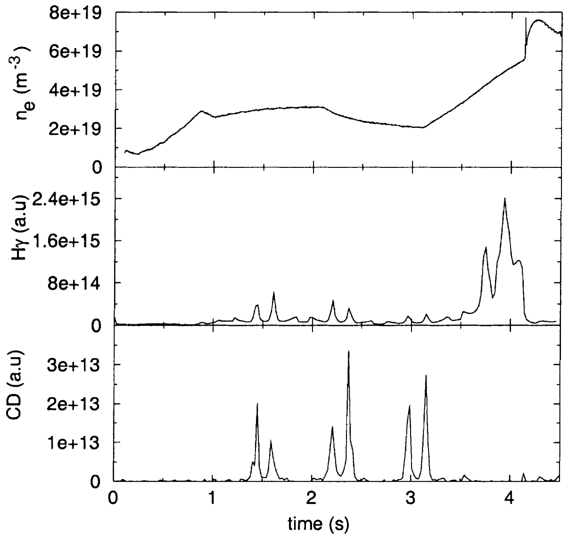

Fig. 1. Line-averaged density (on top) and spatially resolved CD band and D_γ emission (at bottom) in the Ohmic standard discharge (#12217). The spectroscopic signals are plotted vs time. Using a rotatable mirror, the line-of-sight is scanned over the whole divertor. The intensity maxima occur when the inboard divertor is sampled.

D_γ signal. In the recombining divertor plasma, the CD emission is completely extinguished. The extinction may have one of the following reasons:

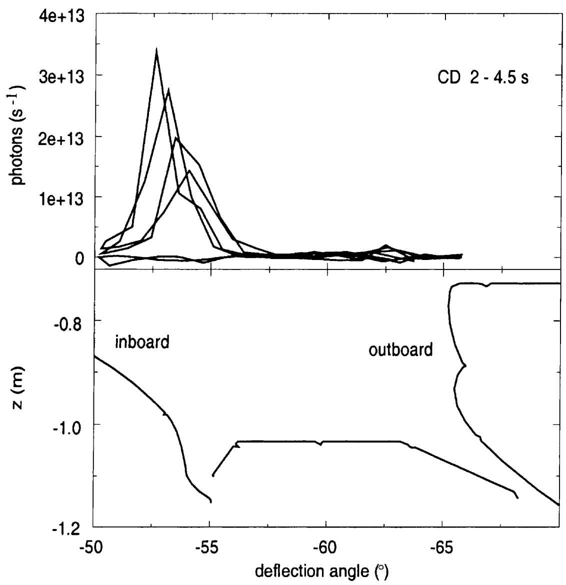

Fig. 2. Spatially resolved CD band emission in the Ohmic standard discharge (see Fig. 1 for time traces). The CD band intensity is plotted vs the deflection angle of the scanning mirror from 2–4.5 s (i.e., for ionising and recombining divertor plasmas). The contour of the divertor is shown below in the deflection angle coordinate.

- In the recombining plasma, the excitation conditions are different compared to the ionising plasma. The CD molecule cannot be excited by electron collisions in such a cold environment.
- The ion flux drops due to the volume recombination and thus the methane influx (the product of the release yield and the ion flux $\Gamma_m = Y_{chem}(T_e)\Gamma_i$) is reduced in the same proportion.
- The temperature in the recombining inboard divertor is so low that the energies of the incident ions are below the predicted threshold for chemical sputtering yield $Y_{chem}(T_e)$. Therefore, the methane influx is significantly reduced.

In the last two cases, the methane influx would be strongly suppressed while in the first case at constant influx the optical emission or dissociation differs compared to the ionising divertor plasma. In the following sections, the three cases will be discussed.

3. Spectroscopic flux measurements at low T_e

If the CD intensity I_{CD} is measured perpendicular to the surface, the methane influx Γ_m can be derived from the relation

$$\Gamma_m = \frac{D}{XB} I_{CD}.$$

Here D denotes the number of methane dissociation acts. X is the excitation rate for the populated level. B takes a possible branching into account (for the considered CD band $B = 1$). Because D and X depend on electron density and temperature, constant plasma parameters must be assumed along the line-of-sight.

In the recombining divertor plasma, the temperature must be lower than 1.2 eV for significant net recombination. Spectroscopic measurements in the inboard divertor showed a minimum electron temperature of $T_e = 0.25$ eV in a neutral beam heated discharge [4]. For this temperature range (0.25–1.2 eV), calculations of D/XB do not exist.

For a single atom, the atomic physics factor S/XB (D was replaced by the ionisation rate S) decreases towards low temperatures. Consider a level which is excited from the ground state. Both the excitation and the ionisation rates decrease since they are threshold processes, but the excitation rate decreases faster since the energy of the excited level is below the ionisation energy.

For the CD molecule, the initial level of the considered transition with an energy of 2.9 eV is occupied by electron collisions from the ground state. The excitation rates decreases rapidly in the recombining plasma. Contrary to the ionisation process, the molecule can be effectively dissociated via charge exchange in the

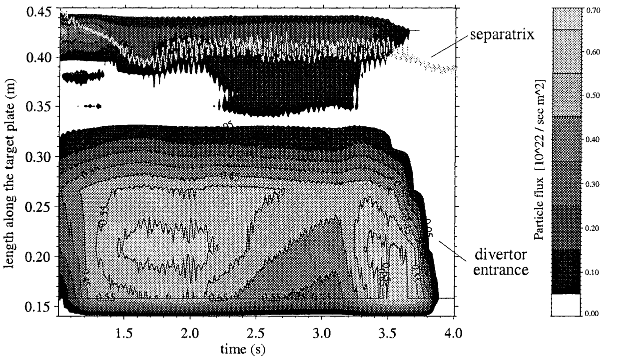

Fig. 3. Particle flux to the inboard target plates measured with Langmuir probes (#13438). The y-axis is the coordinate along the divertor target with zero at the divertor entrance. The separatrix lies at $y = 0.42$ mm. There are two contact regions: the upper one at $s = 0.2$ mm and the lower one near the separatrix. The sharing of the particle flux depends on the line-averaged density (see Fig. 1).

recombining plasma. The corresponding mean free path is of the order of 1 cm. Therefore, D/XB can be expected to increase orders of magnitude in the temperature range quoted above. As a consequence, the CD emission would be extinguished.

4. Comparison with the ion flux

Probe measurements show two separated contact areas in the inboard divertor: the first one near the divertor entrance where magnetic field lines are almost parallel and the second one deep in the divertor where the magnetic separatrix strikes the target plate (Fig. 3). The CD emission behaves quite different when the lines-of-sight strike either of the upper or lower contact area. In Fig. 4, the spectroscopic signals (D_γ, CD) are compared to the ion saturation current of probes located near the strike points of the spectroscopic line-of-sight in the two contact areas. For ionising conditions, the CD emission is nearly proportional to the incident ion flux represented by the ion saturation current. During the density decay (from 2 to 3 s), the flux to the upper contact region is reduced while the flux to the lower region increases. The methane influxes follow these changes until the plasma becomes recombining. The transition from an ionising to a recombining divertor plasma is indicated by the strong increase in the D_γ signal. Simultaneously the CD intensity decays. Later the ion saturation current is also strongly reduced due to the volume recombination. Note that the CD emission drops first deep in the divertor because recombining plasma conditions are reached here at first (compare the D_γ signals). From these experimental results, we conclude that the CD emission starts to decrease before the ion flux goes down due to volume recombination.

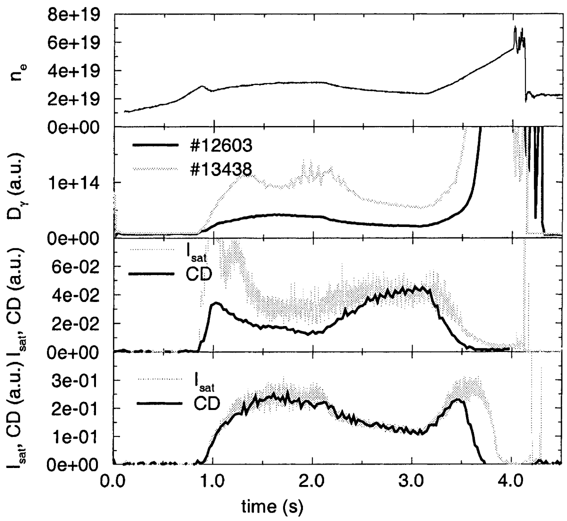

Fig. 4. Comparison of the CD emission with the ion saturation current of Langmuir probes. The following times traces are shown (from top to bottom): line-averaged density, D_γ for two different lines-of-sight, CD emission and ion saturation current from the lower contact area (#13438) and the same from the upper contact area (#12603).

5. Energy threshold of chemical sputtering

In [5,6], the process of chemical sputtering was divided into a volume and a surface process. In the tokamak experiments described above, the heating power was small. The temperature of the divertor targets was well below the peak temperature of the volume process. Thus, the surface process dominates over the volume process in the Ohmic standard discharge. In [5,6], the surface process was described analogous to physical sputtering by a Bohdansky formula but with a threshold energy of 2 eV for deuterium on carbon. This

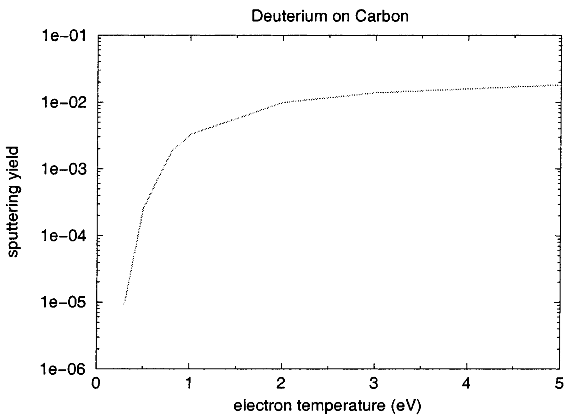

Fig. 5. Total erosion yield (chemical and physical sputtering) for deuterium on carbon according to [5,6]. For the energy distribution of the deuterons, a shifted Maxwellian was assumed.

value for the threshold is supported by laboratory experiments down to 10 eV in which the fit of the experimental data required such as a value (see [6]). Fig. 5 shows the effective erosion yield as a function of the electron temperature. It was obtained by an integration of the sputtering yield with the energy distribution of the deuterons for which a shifted Maxwellian was assumed.

During the density ramp-up, the decrease of the CD band emission was observed with the transition to a recombining divertor plasma as indicated by the increase of the D_γ emission and the decrease of the ion saturation current of the Langmuir probes. The temperature necessary for net recombination is about 1.2 eV. Fig. 5 shows that below 1 eV the sputtering yields steeply decreases.

We conclude that the predicted temperature dependence of the sputtering yield may also explain the observed extinction of the methane influx before the reduction of the ion flux sets in.

6. Summary

We have experimentally shown that the emission of the CD molecule is extinguished in the inner divertor of ASDEX Upgrade. The band emission starts to decrease with the transition to the recombining divertor plasma, i.e., at about 1.2 eV. Two effects can explain this observation. D/XB is expected to strongly increase in the recombining plasma and possibly the methane influx is reduced due to the hypothetical existence of an energy threshold for chemical sputtering. Later, the particle flux to the target is suppressed due to the volume recombination. By this the methane influx is effectively reduced.

Although carbon erosion can be avoided at least in the inboard divertor, for the carbon content of the core this seems to be of minor importance because there is only a weak correlation between the erosion yield in the divertor and the core concentration [2,7].

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